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Reliable Data Transmission Scheme for Perception Layer of Internet of Underwater Things (IoUT)

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ABSTRACT Internet of Underwater things (IoUT) is growing into one of the most important research interests since the last few decades. The primary objective of IoUT is to develop a worldwide network of smart underwater-interconnected objects. It has wide-ranging aquatic applications, including surveillance, pollution reduction, monitoring offshore oil and gas pipelines, disaster prevention, and navigation assistance, making it as important as a terrestrial communication system. The underwater communication channel poses unique acoustic communication challenges that suffer from long propagation delay, low bandwidth, multipath, and fading. IoUT significantly differs from the conventional Internet of Things (IoT) due to disparate environmental conditions under the ocean that require re-designing the underwater communication channel model. In addition to the challenges mentioned above, end-to-end delay and efficient energy utilization are also of great concern. Therefore, in this research paper, diverse attributes of underwater acoustic communication, including the speed of sound, transmission loss, absorption, and ambient noise, are analyzed to design a channel model for underwater communication. These environmental conditions also make underwater acoustic channels highly variable, so efficient resources, including bandwidth and power, are required. Adaptive modulation is proposed to make the communications system efficient by considering the distance between nodes and the signal-to-noise ratio as channel state information. The proposed channel model critically analyzed the CSI factors, results show efficient bandwidth utilization and appropriate power consumption for the well-suited route. The proposed research also aims to reduce end-to-end propagation delay by considering vertical angle-based shortest path (efficient route) in the Multilevel rotating priority MRP-routing algorithm.

INDEX TERMS Bit error rate (BER), Internet of Things (IoT), packet error rate (PER), signal to noise ratio (SNR), Internet of Underwater Things (IoUT).

I. INTRODUCTION

The IoT is defined as integrating people, processes, and technology with sensors to achieve diverse targets. These targets include remote monitoring, smart cities, grid, retail, supply chain, and smart farming [1], [2]. Internet of Underwater things (IoUT) is an emerging class of IoT to introduce underwater smart technology integration. Moreover, it is also expressed in terms of a network comprised of smart underwater objects in interconnected form [1]. National Oceanic and Atmospheric Administration in 2015 found out that 95% of the underwater is still unexplored [3]. Therefore, during the last decade, IoUT has gained a valuable interest owing to the reason that two-thirds of the earth's surface is covered by water [4]. To explore the vast volume of the ocean, smart technology is deployed for underwater communication. The underwater phone is the first device that has been used for this purpose in the past [5].

In underwater communication, signals are propagated via electromagnetic waves, optical waves, and acoustic waves. Electromagnetic waves are mainly affected by attenuation in the water [6]. To overcome this problem, a large size antenna and transmission power at the maximum rate are required [7]. Optical waves are suitable for short-range communication because they scatter and get absorbed rapidly during water propagation. These waves are used to obtain high data rate

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communications (Gbit/s) at short distances [8]. Acoustic waves are less affected by signal absorption as compared to optical and radio waves. Hence, they are more suitable for long-range distances and reliable data transmission [8]. IoUT based applications make underwater acoustic communication systems as important as the terrestrial communication system. To make these applications feasible, underwater acoustic channels need to be characterized. The characteristics of water are different for deep and shallow water. In oceanic literature, the term '*shallow water*' is referred to water with a depth lower than 100 m, while for deeper oceans, the term '*deep water*' is used [9]. The channel conditions in the underwater network are variable due to the water current that leads to a variable bit error rate (BER). These types of channels characteristics have a substantial impact on reliable data transmission.

Generally, worst channel conditions are considered to ensure reliable transmission, but this leads to lower data rates. Underwater nodes have limited energy resources as they need high transmission power. Communication at a lower data rate leads to a significantly higher energy consumption per bit than that is practically possible. To address this issue, many schemes have been proposed in the last couple of years. In [10], researchers proposed an adaptive modulation scheme based on the Bayesian interference algorithm. In [11], [12], authors developed machine learning-based adaptive modulation to resolve this issue. An efficient adaptive scheme using frequency in the neural network [13] and context-aware link adaption [14] has been presented for the physical layer to ensure link reliability and a high data rate. However, channel state information (CSI) at the available receiver is not considered for the link adaption in the techniques mentioned earlier. To calculate CSI, an accurate acoustic communication link and channel model is needed to be developed by taking into account all real factors.

Acoustic communication link of the underwater environment has recently been developed, but it has been implemented in different simulators for specific experiments [13]. Hence, it is difficult for other researchers to regenerate results or compare new protocols to previously published work precisely. In [14], an efficient acoustic communication link is modeled in network simulation tools (NS2). But they did not consider the fading and multipath arrivals of the underwater signal in establishing the link, which are the key factors to be considered in the current communication scenario.

To design a communication system, it is important to have an accurate understanding of the communication channel. It assists in developing signal processing-based techniques and also in the testing and verification of the techniques. In [15], A mathematical model for the underwater channel is developed by considering a few of the real noises that exist in an aquatic environment. Thus, the underwater model is not realistic as it does not consider most of the present noise in the aquatic environment, for example, the noise created by the sea waves and the sea creatures. In [16], an analytical model is developed but it does not draw a conclusion for energy consumption between two nodes which is very important to analyze the system efficiency. In [17], the relationships between capacity and distance are investigated by mathematical communication model, but it does not provide link budget analysis. In [18], researchers have developed models for the deep-water channel by considering very limited measurements. An analytical channel model for shallow water is presented in [19]. In this research work, we propose acoustic communication links of underwater by considering both time variability and multipath effects for underwater acoustic communication to deal with the above-mentioned problems.

Information cached by autonomous unmanned vehicles (AUVs) in safety, environmental monitoring, and emergency applications is crucial. Reliability and latency-sensitive data collection techniques support to meet the smart ocean trends. Earlier data collection techniques and Age of Information (AOI) based optimization approaches are limited to land-based Internet of things (IoT) networks. This is because water has different properties and dynamics, so land-based IoT technologies cannot be stretched to implement in underwater IoT-based systems. In [20], an adaptive, lightweight computational algorithm is presented for two kinds of AUVs that adjust the upper limit of queuing length to ensure the data's freshness. In [21], they provided an analytical solution as a closed-form to determine the outage probability of peak AoI in D/G/1/∞ queuing systems. In [22], the authors presented an efficient algorithm that finds the best path to achieve data freshness but at the cost of delay to cache the information.

The critical challenge in underwater wireless sensor networks (UWSN) is network lifetime stretching and reduction of end-to-end delay for long-term monitoring applications. Underwater network maintenance and replacement by means of the ship are too costly, so it is desirable to have UWSN functioning for a long lifetime. To overcome this issue, priority rotation-based protocol and opportunistic (OR) protocols are currently used but are basically designed for static network topologies. In the case of a dynamic network, some nodes may have high demands to provide service, and due to excessive priority rotations, they can exhaust their batteries. As a result, the network lifetime becomes short, and the performance of the application is compromised. Energy Balancing Protocol (EnOR) protocol is proposed [23], which rotates the forwarding priority level of the candidate node to achieve a balanced energy utilisation. This balanced energy utilization is not followed in other OR routing protocols. The limitation of this technique is that it does not reduce end-to-end delay. In acoustic communication, end-to-end delay is based on propagation delay, mainly caused by horizontal communication links between the sensor nodes on the same depth level, leading to a longer routing path. Therefore, propagation delay is to be reduced by reducing the propagation distance. For this reason, here it is proposed to selects the next forwarding node mechanism. Forwarding node selection is based on the angle between the direction of propagation and its perpendicular. This angle should be smaller than 180 degrees and greater than zero. The triangular inequality theorem supports that the route having an angle in the range 0 to 180 degrees is shorter than the horizontal mean angle nearer to 90 degrees, leading to a smaller propagation distance. Consequently, there is less propagation loss. So, the idea of a smaller propagation distance is being suggested to avoid propagation delay.

Moreover, underwater nodes are often battery-operated, and acoustic modems operate in half-duplex mode. It is extremely important to design an energy-efficient communication system. To adopt a modulation scheme according to the channel condition is a key solution to make the communication system energy efficient and maximize its channel capacity. Conventionally, Signal to Noise (SNR) is considered a CSI parameter to find the link quality. To consider nearby node distance (as it is variable), in addition to SNR as a parameter of CSI, is one novel aspect of this research. Hence proposed acoustic channel model for the perception layer of IoUT is presented in this paper, which has the following contributions in the research field.

1. To calculate link reliability by considering various factors and their impact on IoUT.
2. Critical analysis of the CSI factor is done to reduce the number of re-transmissions.
3. To conform less propagation delay by considering vertical angle-based shortest path and achieving reliable communication.
4. Multilevel rotating priority MRP-routing algorithm ensures efficient bandwidth utilization and proper power consumption for the appropriate route.

The rest of the paper is organised as follows: Section 2 presents the proposed scheme for the underwater acoustic link. Section 3 presents the channel modelling for underwater acoustic (UWA) communication. A comprehensive mathematical model for underwater acoustic communication is presented to investigate power consumptions trade-off with transmission range and provide link budget analysis and CSI for deep and shallow water. Experimental results are also provided to validate the channel model based on commercially available modems, i.e., Link Quest UWM1000 for shallow and Link Quest UWM10000 for deep water. Section 5 presents the assessment and performance evaluation of the proposed model, and finally, section 6 concluded this research work.

II. PROPOSED SCHEME

Figure 1 shows the complete process of communication. The sender generates a message, encodes it with any encoding scheme, and passes it on the channel. Channel noise may be added. On receiving side, the decoder decodes it, and the receiver uses it if it is error-free and sends ACK to the sender in case of successful transmission and NACK in otherwise. The same analogy is true for underwater communication. Its communication model consists of three layers.

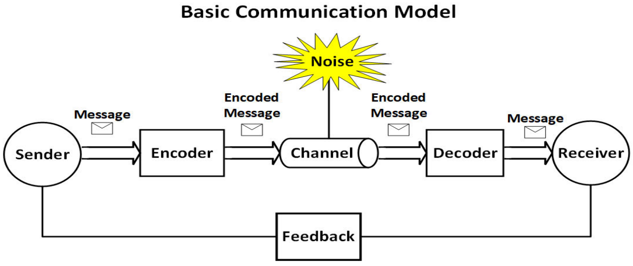

FIGURE 1. Basic communication system.

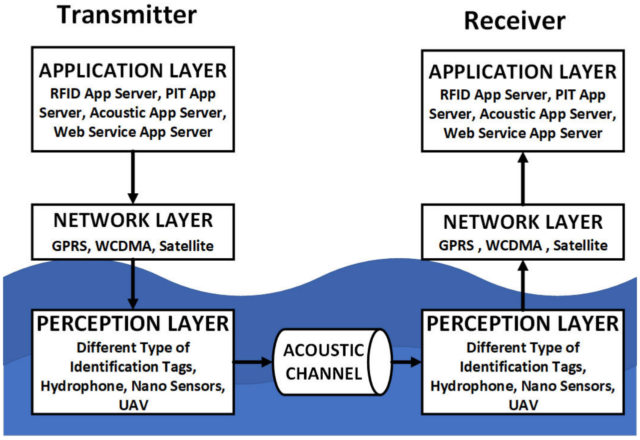

FIGURE 2. Block diagram representation of considered UWAN model.

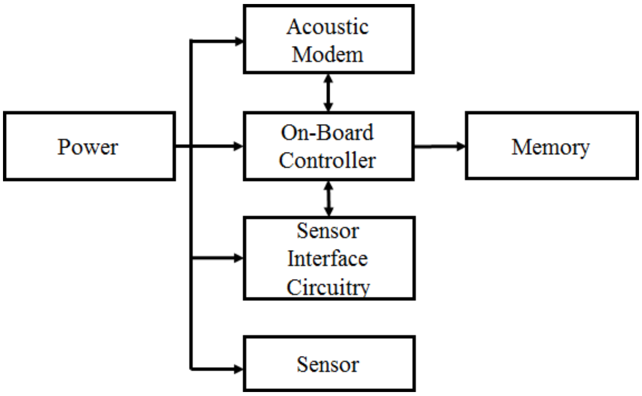

FIGURE 3. Basic architecture of UW -sensor node.

Figure 2 shows the system model of underwater communication. This system mainly shows two components, i-e, Transmitter, and Receiver. The flow of information on the transmitter side will be from the application layer to the network and then to the perception layer. On the receiver side, it will be from the perception layer to the network and then to the application layer. The components of the perception layer are set up sparsely because their deployment is costly [21]. These sensors sense, store, and forward the upcoming information to sink nodes at the network layer. The network layer receives information from the perception layer and then transmits it to the application layer. Application Layer is responsible for providing service by using available concerning intelligent solutions. At the perception layer, the acoustic channel shows that all communication is carried out underwater. For communication purposes, the perception layer uses different types of underwater sensors (UW-sensors), such as Acoustic Tag, Radio Tag, and PIT Tag. It also uses hydrophones, nano-sensors, and UAVs. UW-sensors nodes require more storage capacity as compared to the terrestrial sensor nodes because UW-sensors require caching due to the irregular nature of the communication channel [7].

The basic architecture of the UW-sensor node is shown in Figure 3. It mainly consists of controller/CPU, acoustic modem, power supply, sensor or oceanographic instrument memory, and interfacing circuitry. The acoustic node operates in half-duplex mode. Controller gets data from the sensor and processes it. It can store data at an onboard memory unit for future correspondence.

The sensor node can transmit processed data on the network by switching modem to transmit mode. This whole electronic circuitry is mounted on a frame protected by Poly Vinyl Chloride (PVC) due to underwater environmental conditions.

Underwater acoustic channel quality may vary within very small time intervals [24]. This nature of the UWA channel causes large BER. A research study reveals that the average SNR of a UWA channel is nearly 9 ∼ 5.7 dB for the time duration of 0.5 minutes, and it is nearly 9 ∼ 3.5 dB for a time duration of less than 1.5 minutes [25]. Many factors are involved that directly affect the communication performance of underwater acoustic channels. These factors include path loss, noise, multipath, and Doppler spread. Packet loss and high error probability in the acoustic channel are the results of the factors mentioned earlier [26]. The underwater environment is complex and dynamic. The rapid change in its environmental conditions makes the transmission channel more complicated. UWA channel modeling is difficult and complex because the UWA channel is time-varying and frequency-dependent. Moreover, an analytical study shows that the soundscape in warm shallow water is spontaneous [27]. These unique features make the Gaussian noise process impractical for their characterization while it is very suitable for digital RF communication systems. Establishing a UWA link is relatively challenging due to the factors like multipath propagation, absorption, scattering, water-salinity, dispersion, and physical obstruction. Designing and developing a UWA channel to achieve reliable communication is more challenging for shallow water than deep water. Factors like temperature gradients, surface noise, and the influence of multipath propagation due to reflections have more impact in shallow water than deep water [28].

It is required to predict the behavior of underwater acoustic channels to avoid the failure of underwater monitoring missions. For acoustic waves, huge diversity can be seen in the underwater channel as a propagation medium [29], [30]. Therefore, in this section, key indicating attributes of underwater channel models are discussed. The factor of white Gaussian noise is taken into account by integrating transmission support to the Gaussian channel.

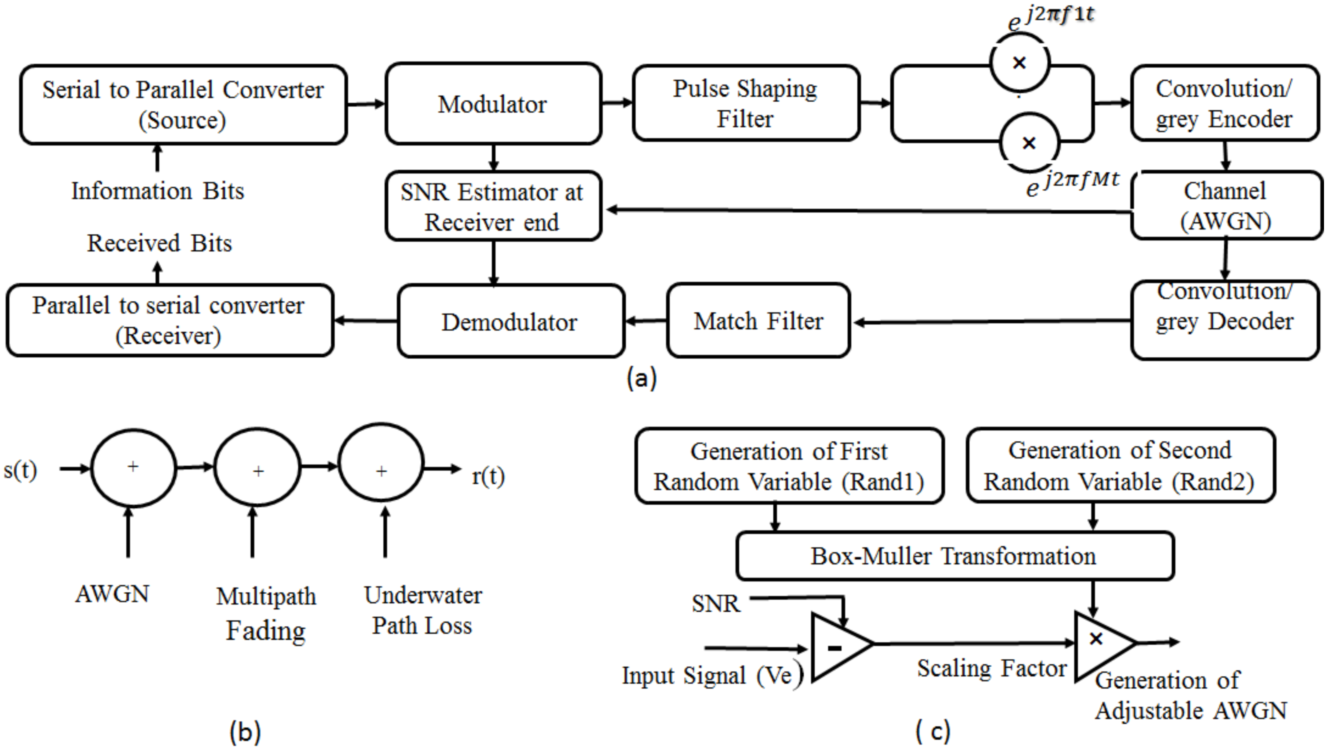

FIGURE 4. Descriptive model for the acoustic link (a) UWA channel link (b) Conceptualization of an underwater channel (c) Internal Structure of UWA channel.

Moreover, multipath effects, especially the multipath fading channel, is the key constraints in underwater communication that need to be addressed. At last, the path losses module must be taken into account that is brought together by the aquatic surroundings. Path losses are the losses due to absorption, scattering, and geometrical effects like diffractions and reflections [31]. SNR and the available bandwidth range of the channel can be determined via these path losses [32]. Unlike the terrestrial channel, the multipath formation in underwater has a diverse mechanism. The phenomena of multipath propagation in water have numerous means that are truly dependent on the depth and range of communication.

Additive white Gaussian noise (AWGN) is used as a noise model in wireless communication systems to reflect the impairment caused by the linear addition of white noise [33]. The underwater channel has a vast diversity of propagation mediums for the acoustic waves [34], [35]. In an aquatic channel, Gaussian noise originates from various sources such as thermal noise, shipping noise, and ocean turbulence. Multipath fading and Path losses are the major constraint of the underwater communication channel. To make AWGN channel appropriate for underwater acoustic communication needs to construct a mathematical model for the modulated signal. Gaining insight into the underlying behavior of the system, a mathematical model for the modulated signal needs to be constructed that takes account of multipath fading and path loss by the aquatic environment. The conceptual representation of the aquatic channel is represented in Figure 4(b). The following equations show the mathematical expression for noise generation.

$$PRC\,(f) = \frac{\cos\,(\pi\alpha ft)}{1 - (\pi\alpha ft)^2} \tag{1}$$

$$X = \ln\,(Rand1)\,.\cos\,(2\pi Rand2) \tag{2}$$

$$Noise\ generator = 10^{\left(\frac{level}{20}\right)} X\ Noise \tag{3}$$

where,

$$level\ (dB) = \text{Input signal (dB)} - \text{SNR(dB)} \tag{4}$$

Equation (1) represent the root raise cosine filter. Where f is frequency and α is roll off factor. Inter-symbol interference (ISI) reduction is the main objective of using the root-raised cosine filter. In a certain bandwidth, it is also practiced to send the data that ultimately impact the BER value of all corresponding modulations.

Here Box-Muller transform is applied on two (Rand1 and Rand2) randomly generated values; noise is generated by using the expression mentioned above in Equation (2), and finally, AWGN is adjusted according to the value of level that is calculated by using Equation (3). This model is designed by using Coppens [36], derived expression for an aquatic environment. Figure 4 (c) shows the internal structure of the AWGN channel for UWA communication.

To represent the delay factor of signal transmission due to the phenomenon of multipath fading and path loss effect, timing errors to input signals have been introduced; then, they are passed through the channel. Finally, all signals are combined afterward, and the output signal is taken from this channel. This output pattern exhibits like the real underwater channel outputs.

Reverse operations are performed on the received signal at the receiver side. To recover the signal back into the frequency domain, fast Fourier transform (FFT) is applied. Then demodulation and de-interleaving are employed on the received signal. Finally, the output signal is achieved after the decoding process.

III. MATHEMATICAL MODELLING OF ACOUSTIC CHANNEL FOR IOUT

This section first presents the acoustic channel's characterization for IoUT and then discusses the estimation of link reliabilities through the underwater channel model. Here, we investigate the channel models for underwater environments. The models aim to calculate the packet error rate (PER). The calculation of PER depends on BER, and it is estimated by using SNR. In IoUT reliable data, the transmission is a challenge due to variable channel conditions.

Electromagnetic waves propagate poorly in underwater. Acoustics waves are the best medium for underwater communication systems [37]. Water being a transmission medium poses various challenges like propagation delay, signal to noise ratio, transmission delay, spreading loss, propagation sound, ambient noise, and absorption loss [38], [39]. Change in the speed of sound is also suffered from various underwater environmental factors like temperature, salinity, and pressure [40]. These aforementioned factors are studied before the construction of the channel model.

$$\alpha\,(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003 \tag{5}$$

$$SS_{\text{spherical spreading}} = 20\log(r) \tag{6}$$

'r' is the transmission range in meters, and normally it is 70 meters and 130 meters for shallow or deep water, respectively [41].

When a signal travels from source to destination, some loss in signal strength occurs, which is called spreading loss [42]. The spreading loss in dB is specified as

$$PL_{spreading} = k \times 10\log(r) \tag{7}$$

Here 'k' is the spreading factor, and its value is 1 for cylindrical spreading and 2 for spherical spreading, whereas 'r' is the transmission range.

Transmission loss is defined as the reduction of sound intensity when it travels from source to receiver [43]. It depends on the transmission range and frequency [44]. According to Thorp formula [35], [45], transmission loss in dB is stated as:

$$TL = SS + \alpha\,(f) \times r \times 10^{-3} \tag{8}$$

where attenuation factor α is expressed in dB and 'f' is the frequency in kHz.

When sound waves travel in water, viscous friction and ionic relaxation occur, which becomes the cause for the loss of energy in the sound signal. This absorption of heat energy in water is called absorption loss [29]. It is expressed as:

$$PL_{absorption} = \alpha \times r \times 10^{-3} \tag{9}$$

'α ' is attenuation and is represented by Equation 5.

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Multipath propagation is mainly caused by the refraction in the water and the reflection of the wave at the surface, bottom, or at any object. Salinity, temperature, and depth have a strong impact on the propagation speed of an acoustic signal in underwater. Its speed is approximately 1500 m/sec [25].

To calculate the acoustic wave propagation speed in the water, which is purely based on salinity, temperature, and depth of the sea, Equation (10).is used in [46].

$$\begin{aligned} C = {} & 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 \\ & + 2.374 \times 10^{-4}T^3 + 1.340\,(S - 35) \\ & + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 \\ & - 1.025 \times 10^{-2}\,(S - 35) \\ & - 7.139 \times 10^{-13}D^3 \end{aligned} \tag{10}$$

where T is the temperature, S is the salinity, and D is the depth in the above Equation (10).

In UWSN, the accumulative sum of turbulence noise ($N_t\,(f)$), shipping noise $N_s\,(f)$, wave noise $N_w\,(f)$And thermal noise $N_{th}\,(f)$ is characterized as ambient noise [2].

$$N\,(f) = N_t\,(f) + N_s\,(f) + N_w\,(f) + N_{th}\,(f) \tag{11}$$

where turbulence noise is

$$10logN_t\,(f) = 17 - 30\log(f) \tag{12}$$

Shipping noise is:

$$10logN_t\,(f) = 40 + 20\,(s - 0.5) + 26\log(f) \tag{13}$$

Wave noise is:

$$10logN_w = 50 + 7.5\sqrt{w} + 20\log\,(f) - 40\log(f + 0.4) \tag{14}$$

Thermal noise is:

$$10logN_{th}\,(f) = -15 + 20\log\,(f) \tag{15}$$

Noise approximation level can be calculated by using the following Equation 16 [2].

$$N_{level} = 50 - 18\log\,(f) \tag{16}$$

To calculate the link reliability on IoUT, we aim to calculate the PER of links as PER refers to the reliability of links. Underwater nodes are mobile and have variable distances between them due to water current. These features of IoUT lead to variable PER.

Let γ be the SNR. The SNR can be divided into four parts [9], [27] and can be expressed as follows:

$$\gamma = S_{level} - T_{loss} - N_{level} + D_{index} \tag{17}$$

where S_{level}, T_{loss}, N_{level} 1, and D_{index} are the source level, transmission loss, noise level, and directivity index, respectively. The unit of each factor is dB.

The source level is defined as the effective level of sound. In [47], the source level is expressed by following Equation (18).

$$\mathrm{S_{level}} = 10[\log(\mathrm{I}) - \log\left(0.67 \times 10^{-18}\right)] \tag{18}$$

where I is transmitted signal intensity, it is different for shallow water and deep water. In [48], it is expressed by following Equation (19) and Equation (20).

$$I_s = \frac{P}{2\pi r^2} \tag{19}$$

$$I_d = \frac{P}{4\pi r^2} \tag{20}$$

Equation (19) shows I for shallow water, while Equation (20) shows I for deep water. P is transmitter power in watt, and r is the radius of the sphere in the meter. Using equations 18 and 19, we can compute the source level for shallow water, which is expressed by Equation (21).

$$S_{level} = 10\left[\log\,(P) - \log\left(2\pi r^2\right) - \log\left(0.67 \times 10^{-18}\right)\right] \tag{21}$$

Using equations 18 and 20, we can compute the source level for deep water, which is expressed by Equation (22).

$$S_{level} = 10[\log\,(P) - \log\left(4\pi r^2\right) - \log\left(0.67 \times 10^{-18}\right)] \tag{22}$$

Transmission Loss is a decrement in sound energy when it travels from the sending node to the receiving node. In [47], transmission loss is expressed by following Equation (23).

$$T_{loss} = 20log(d) + \alpha(f) \times d \times 10^{-3} \tag{23}$$

Here d is the distance in the meter is the frequency in kHz, and $\alpha(f)$ is the absorption coefficient in dB/km. Throp formula [49] is used to calculate the absorption coefficient. It is expressed by Equation (5). Noise level is expressed in terms of turbulence noise, shipping noise, wave noise, and thermal noise [2]. In [17] provide the approximation of noise level. It can be calculated by using Equation (16).

An underwater hydrophone is omnidirectional so that DI can be set as 0. By combing these Equations, we can compute SNR by using Equation (24) for shallow water.

$$\begin{aligned} \gamma = {} & 10\left[\log\,(P) - \log\left(2\pi r^2\right) - \log\left(0.67 \times 10^{-18}\right)\right] \\ & - 20\log\,(d) - \alpha\,(f) \times d \times 10^{-3} - 50 \\ & + 18\log f \end{aligned} \tag{24}$$

BER is highly dependent on the modulation scheme. For underwater environments, eight phase-shift keying (8PSK)

TABLE 1. Channel state information (CSI) at node G.

Path 1					Path 2					Path 3				
Route	**CSI Parameters**				**Route**	**CSI Parameters**				**Route**	**CSI Parameters**			
Source: G	**Distance**	**SNR**	**BER**	**PER**	**Source :G**	**Distance**	**SNR**	**BER**	**PER**	**Source :G**	**Distance**	**SNR**	**BER**	**PER**
E	200	42	1.57 x 10^{-5}	.690	D	300	49.481	2.81 x 10^{-5}	.0.93	H	300	49.481	2.81 x 10^{-5}	0.930
B	200	42	1.57 x 10^{-5}	.690	A	200	42	1.57 x 10^{-5}	.69	F	300	49.481	2.81 x 10^{-5}	0.930
Sink: A	400	37.202	4.76 x 10^{-5}	0.310	**Sink**:D	400	37.202	4.76 x 10^{-5}	0.31	C	200	42	1.57 x 10^{-5}	0.690
--				--	--				--	**Sink**: H				--

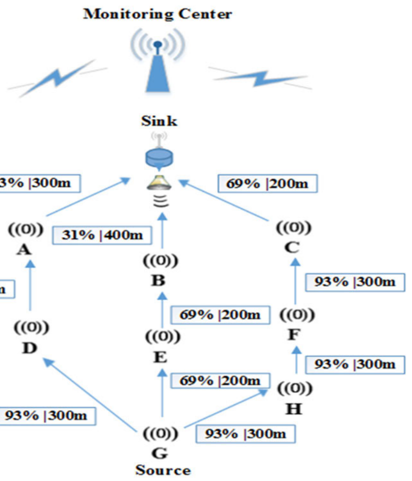


FIGURE 5. Simulation scenario.

is selected because 8PSK showed the best performance in underwater acoustic sensor networks [50] as BER calculation depends on

SNR, the fluctuation in received signal power is different for shallow water and deep water. Because in shallow water, multipath fading occurs due to signals reflection from the surface and the bottom and objects in the water. But in deep water, it occurs due to ray bending. In [51], [52], they suggested Rayleigh or Rician model for signal propagation. Rayleigh fading is a suitable model for exhibiting the multi-path effect in shallow and deep water; that is why the Rayleigh fading channel is selected [53]. Minor fading effects are often exhibited as Rayleigh or Rician fading [51], [52], while other investigations propose K-distribution [54] or Weibull distribution [17] for the above-mentioned purpose. In [55], Urick suggests the Rician model to exhibit the amplitude variations in the aquatic atmosphere. In [53], the authors propose a Rician distribution to exhibit a blowy shallow water channel model. To analyze the minimum transmitted power in our research work, we have considered both Rician and Rayleigh fading models. The BER of BPSK in a Rayleigh fading channel is presented in [56].

For shallow water having BPSK in the Rician fading channel [57], the average BER can be computed using Equation (25). For deep water having BPSK in the Rayleigh fading models[53], the average BER can be computed by using Equation (26).

TABLE 2. System parameter.

P	Target successful delivery Probability
PBSK	Modulation Scheme
Rayleigh Fading [60]	Channel Model
Simulation Parameter according to Link Quest UW Modem [62]	
Packet size	30KB
F	Frequency 10KHz
PT	Transmitter Power [1-40] watt

$$BER\,(\gamma) = \frac{1}{2}\left(1 - \sqrt{\frac{10^{\frac{\gamma}{10}}}{1 + 10^{\frac{\gamma}{10}}}}\right) \tag{25}$$

$$BER\,(\gamma) = \frac{1}{2} erfc \sqrt{\frac{K 10^{\frac{\gamma}{10}}}{K + 10^{\frac{\gamma}{10}}}}) \tag{26}$$

When the SNR is equal to γ, then BER (γ) is predicted as the number of bit errors per unit time over a communication channel. Now PER can be calculated by using BER [58]. Where 'Y' is the number of bits in a packet. PER is given by Equation (27).

$$PER = 1 - (1 - BER)^{y} \tag{27}$$

In consideration of channel models, if transmitter power is P, the transmission distance is d, and frequency is f, the value of the SNR is γ for IoUT. Then using the SNR γ, we can calculate the reliability (i.e., the BER) for IoUT. In a precise way, one can say that if the transmitter power is given with transmission distance and frequency, a quick and accurate way of estimating the reliability in UWSNs can be provided by the channel model. It can also be used to compute the energy efficiency of any FEC scheme by using Equation (28) [49].

$$E_{eff} = \frac{n - k}{n + \alpha}(1 - PER) \tag{28}$$

In the case of the FEC scheme, n-k is payload bits, α is header bits, and k is parity bits.

TABLE 3. Characterisation of channel model.

Depth (m)	Temperature (o_C)	Salinity (ppt)	Frequency	Cylindrical Spreading Loss(dB) Eq7	Spherical Spreading Loss(dB) Eq7	Transmission Loss Eq 8 Where r=70m	Absorption Loss Eq9	Propagation Loss Eq10
20	18	0.0374	10	13.010	26.020	84.971	0.237	1475.390
30	15	0.0360	15	14.770	28.540	84.972	0.356	1466.030
50	10	0.0353	20	16.980	33.960	84.974	0.593	1448.160
Depth (m)	**Temperature (o_C)**	**Salinity (ppt)**	**Frequency**	**Cylindrical Spreading Loss(dB)**	**Spherical Spreading Loss(dB)**	**Transmission Loss**	**Absorption Loss**	**Propagation Loss**
500	8	0.0351	10	20.790	41.580	100.213	1.424	1446.620
1000	6	0.0490	15	21.130	42.260	100.215	1.543	1446.410
1500	4	0.0340	20	21.760	42.520	100.216	1.780	1445.510

TABLE 4. Transmission energy consumption for shallow and deep water.

Shallow Water		Deep Water	
Distance between two Nodes	Power Consumption	Distance between two Nodes	Power Consumption
50	0.140mw	500	12w
150	0.280mw	600	14.400w
200	4.20mw	700	16.800w

TABLE 5. Reception energy consumption for shallow and deep water.

Shallow water		Deepwater	
Distance between two Nodes	Power Consumption	Distance between two Nodes	Power Consumption
50	.190mw	500	14w
150	.380mw	600	16.400w
200	6.200mw	700	17.800w

TABLE 6. Information of link budget for different ranges.

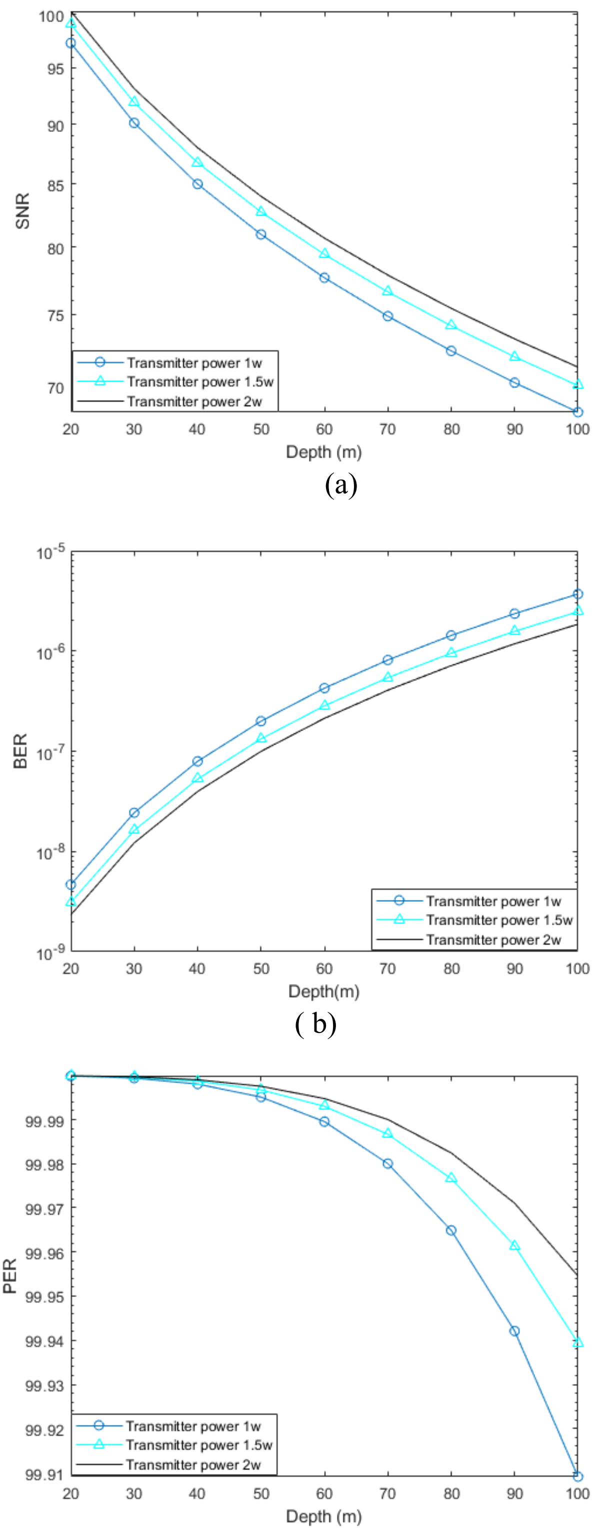
Range	Transmission Loss	Noise Level	SNR	BER	PER
100	46.2	32	42	1.57x10-5	.690
300	50	32	49.4	2.817x10-5	0.93
400	52.5	32	37.2	4.76x10-5	0.31

IV. EXPERIMENTAL SETUP

An underwater acoustic network with two nodes (source, sink) is considered. The frequency at which these nodes communicate is 10KHz, and transmitter power is considered 2Watts.

Figure 5 shows the scenario as mentioned earlier. It shows three possible paths from the source sensor node (i.e., node G) to the sink node (i.e., node on the surface of the water). Each link is labeled with the link distance and the link budget. Link distance is the calculated angle between its vertical direction and direction of propagation. Moreover, it does not depend on location information as it is directly accessible by directional antennas.

Table 1 shows that two nodes having the largest distance are less prone to error. By selecting higher order modulation scheme, a high data rate can be achieved. A scenario is being considered to emphasize the reliability of the link between a pair of connected nodes in UWSNs. Analysis of the link budget reveals that the shortest path is not always the most reliable path. Based on multilevel priority, the shortest path routing protocol is required to resolve this problem. The basic idea to choose this MRP-routing algorithm is that the best next hop is selected in comparison to multiple priorities. These priorities are the primary priority and secondary priority. Here primary priority defines distance, and residual energy and secondary priority refer to link quality. Node with a long network lifetime and less delay is selected as the best next-hop. Also, Link distance is of great importance, and these two things fulfill the criteria for primary priority. If multiple candidates' nodes compete with the same primary priority, link quality (secondary priority) plays an important role. As MRP not only shortens the delay but also reduces network energy consumption. In other words, by using primary and secondary priority mechanisms, MRP selects the reliable transmission route based on link quality to reduce the number of re-transmissions and it ensures the efficient utilization of bandwidth.

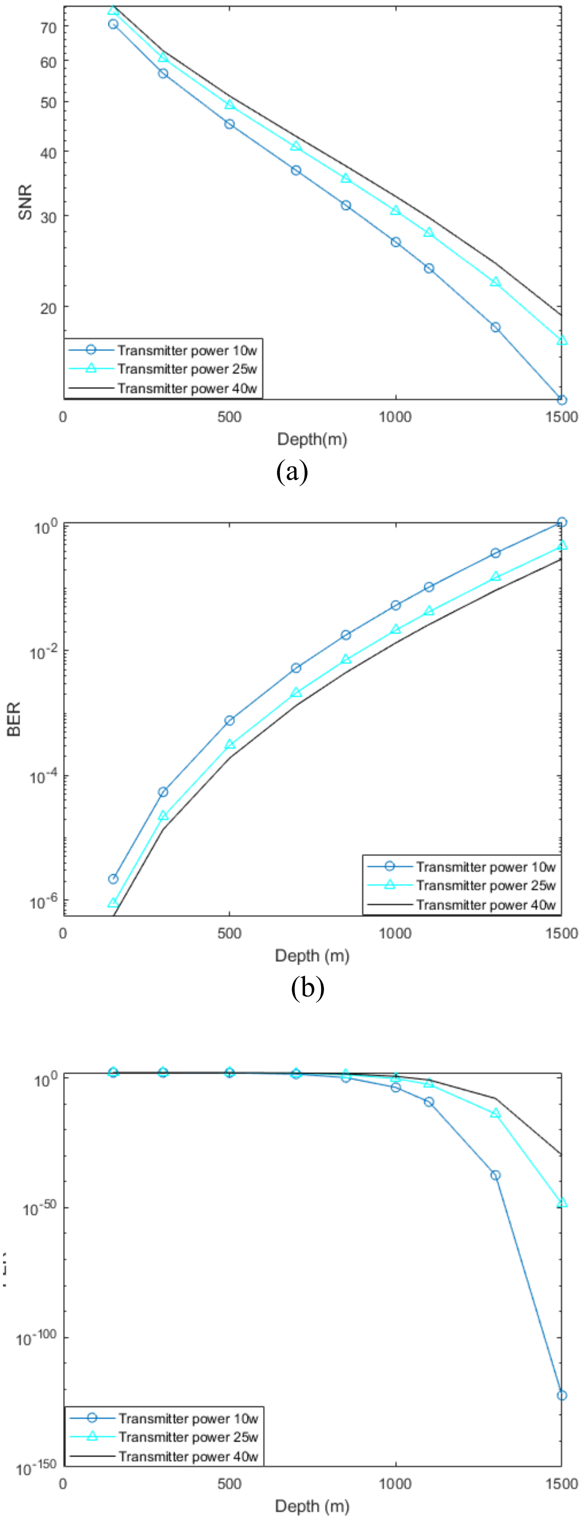


(a)

(b)

(c)

FIGURE 6. Performance analysis of IoUT channel for shallow water. (a) Simulation of the Signal-to-Noise Ratio (SNR) performance for shallow-water when the channel models are applied to different transmitter powers (1–2W) and distances (20–100 m). (b) Simulation of the Bit-Error-Rate (BER) performance for shallow-water when the channel models are applied to different transmitter powers (1–2W) and distances (20–100 m). (c) Simulation of the Packet Error Rate (PER) performance for shallow-water when the channel models are applied to different transmitter powers (1–2W) and distances (20–100 m).



(a)

(b)

(c)

FIGURE 7. Performance analysis of IoUT channel for shallow water. (a) Simulation of the Signal-to-Noise Ratio (SNR) performance for shallow-water when the channel models are applied to different transmitter powers (20–40W) and distances (100–1500 m). (b) Simulation of the Bit-Error-Rate (BER) performance for shallow-water when the channel models are applied to different transmitter powers (20–40W) and distances (100–1500 m). (c) Simulation of the Packet Error Rate (PER) performance for shallow-water when the channel models are applied to different transmitter powers (20–40W) and distances (100–100 m).

Channel state information at node 'G' is depicted in table 1, which helps node 'G' in the adaption of modulation scheme based on link budget analysis and the distance of nearby node. As channel conditions are continuously varying so to achieve standard output fixed modulation scheme is not suitable. Hence, an adaptive modulation scheme is proposed. Transmitter uses CSI to select modulation scheme. CSI carries information about SNR, BER, PER, and distance for the last transmission of the corresponding link between nodes. At the transmitter, a reverse channel is needed. Table 1 shows that Route 2 is less prone to error. In such a case, data will be preferably transmitted over this link with a higher-order modulation scheme as lower-order modulation schemes are more immune to noise. They are selected to transmit a low data rate for a given bandwidth. For higher data rates high order modulation schemes are preferred.

On the other hand, Route 2 is longer than Route1. As route 2 is less noisy, so there are very high chances of successful transmission in a single attempt. If more than one routes have the same length then a less noisy route is selected to achieve reliable data transmission.

Underwater acoustic communication is suffered from inadequate bandwidth that is influenced by transmission range and frequency. In recent years, many researchers have addressed efficient bandwidth utilization [59], [60], propagation delay [61], [62], energy efficiency [8], [63], deployment policies [48], [64], and routing algorithms [65] but there is very less research work to deal with aforementioned peculiar features for IoUT. These features have a strong impact on link reliability. In IoUT, the transmission energy consumption is 100 times greater than the reception [66]. Numerous re-transmissions will ultimately result in long propagation delay, inefficient bandwidth utilization, and power consumption. So, link reliability is a serious issue for IoUT that needs to be addressed in current research. Unlike the existing research work, a channel model is designed to estimate link reliability by considering all the factors mentioned above to calculate CSI accurately.

This approach increases the reliable data transmission over the acoustic link with efficient bandwidth utilization. Reliability in data transmission reduces the number of re-transmissions to decrease propagation delay and energy consumption. Hence overall efficiency of the system improves by this strategy.

There are three possible routes from node 'G' to sink node, and Route1 is the shortest route. If distance as a single factor is considered, it will be the best route, but this route is more prone to error, as shown by the PER parameter of CSI. By selecting Route1 for communication, it will be done via lower order modulation scheme as it is more immune to noise. This will lead to communication at a low data rate. It requires more energy consumption per bit transmission. It is also inefficient utilization of available bandwidth. This route poses a high PER which increases the chances of request for packet re-transmission. Ultimately introduces a delay in data transmission.

V. ASSESSMENT AND PERFORMANCE EVALUATION

In this section, the results of the proposed communication system for IoUT are discussed. The simulations were conducted using MATLAB. Here, we select the BPSK modulation scheme and Rician Channel Model for shallow water. We set parameters according to commercially available acoustic modems i-e Link Quest UWM1000. We adjust operating frequency 10 kHz, Packet size 50 bytes, and transmission range 100m. Transmitting, receiving, and idling power consumption is 1w-2w, 10mw, and .1w, respectively. Table 2 shows simulation parameters of underwater WSN. Table 3 shows the characterization of the channel model. Transmission loss is inversely related to transmission distance as expressed in Equation (8); when transmission distance increases, transmission loss will decrease, and ultimately SNR will decrease; the same is true for transmission power.

It is also investigated that SNR has a direct relation with transmitter power. We calculated SNR and then BER. The packet delivery ratio is calculated by applying packet size on BER. Performance analysis of channel is done by considering three factors (i) SNR (ii) BER (iii) Packet delivery ratio. Figure 6 (a) and 7 (a) shows that SNR is inversely proportional to transmission distance.

Equation (17) expresses that SNR comprises four main terms; transmission loss, source level, noise level, and directive index. Transmission loss has a direct impact on SNR. This model also analyses the behavior of BER against different transmission distances. BER has a direct relation with SNR, but SNR has an inverse relation with transmission distance. Figures 6 (b) and 7 (b) plot the BER versus transmission distance and show that BER is high for smaller transmission distances and low for others. BER is inversely related to the transmitter power, and simulation results for packet delivery ratio show that their behavior is similar to BER, as shown in Figures 6 and 7(c).

Here a proposed model is extended to determine the entire energy consumption to send a packet over the network. The energy consumed at a node is calculated by knowing the values of transmission power (Tp), Packet size Pl, data rate (DR) of the acoustic channel, and d distance between two nodes.

$$\sum \text{Total} = \sum \text{tx} + \sum \text{rx} \tag{29}$$

where $\sum$ tx is the amount of energy consumed when a data packet is transmitted and $\sum$ rx is the amount of energy consumed when a data packet is received. Where $\sum$ Total is the total amount of energy consumed while transmitting a packet from node N-1 to the nth node. The mathematical expression is given as follows [3].

$$Etx = (Ptx * Pl * d)/D \tag{30}$$

where Ptx is transmission power, and Pl is packet size, d is the distance between two nodes, and DR is the data rate.

TABLE 7. Analysis of BER w.r.t different modulation.

S.No	SNR	BER (QAM-256)	BER (QAM-64)	BER (QAM-16)	BER (QAM)	BER (PSK-256)	BER (PSK-64)	BER (PSK-16)	BER (BPSK)
1	.850	0.238	0.180	0.122	0.135	0.354	0.320	0.254	0.0600
2	1	0.236	0.178	0.118	0.130	0.351	0.317	0.249	0.0565
3	3	0.197	0.137	0.0776	0.0793	0.333	0.293	0.202	0.0229
4	3.50	0.187	0.128	0.0673	0.0672	0.327	0.285	0.190	0.0170
5	6.50	0.132	0.0755	0.0220	0.0172	0.296	0.246	0.114	0.00140
6	7	0.124	0.0683	0.0170	0.0125	0.293	0.238	0.101	0.0008
7	7.50	0.116	0.0594	0.0128	0.00870	0.286	0.230	0.090	0.0004
8	10	0.078	0.0270	0.00180	0.00870	0.264	0.196	0.039	0
9	12	0.0537	0.0100	0.000200	0	0.241	0.163	0.0140	0
10	13	0.0409	0.00540	0.0000	0	0.233	0.148	0.00740	0

TABLE 8. Switching thresholds level.

S.No.	SNR	Modulation
1	SNR<3	BPSK, QAM-16
2	3.5<SNR<7.5	PSK-16, QAM-64
3	SNR>23	PSK-64, QAM-256

The mathematical expression for reception energy is given as follows [67].

$$Erx = (Prx * Pl * d)/DR \tag{31}$$

For transmission and reception energy consumption of shallow water, we set parameters according to the commercially available acoustic modem, i.e., Link Quest UWM1000 for shallow water. To find transmission and reception energy consumption for deep water, we set parameters according to commercially available acoustic modem i-e Link Quest UWM10000 for deep water. Table 4 and Table 5 show transmission and reception energy consumption, respectively. Both Equation (30) and Equation (31) show that transmission and reception power are directly proportional to transmission distance. Tables 4 and 5 show that when distance increases, more power is required. It can be concluded that if nodes are deployed sparsely, they should be potentially heavier for better performance, which is ultimately more expensive. These results indicate the trade-off between performance and cost. Here, Table 6 shows link budget analysis w.r.t different ranges.

Detailed simulation results are carried out by using the proposed scheme in section 2 shown in Table 7. In Table 8, comparative analysis finds out that for operating BER of 10^-3, there are Binary Phase-shift keying (BPSK) and quadrature amplitude modulation (QAM-16) that gives the desired performance at SNR below 3dB. PSK-16 and QAM-64 can also be recommended for BER 10^-3 dB while SNR should be in the range of 7 7.5 dB to 13 dB.

Lower order modulation techniques perform well in case of high SNR while higher order modulation technique serves better in the case of low SNR. The performance comparison of different modulation schemes is based on BER.

VI. CONCLUSION AND FUTURE RECOMMENDATIONS

In this research work, useful information about IoUT, its application, and its challenges are discussed. The paper also provides a MATLAB simulation for different attributes of underwater acoustic communication system. The results from these observations can further be used to current research may encounter new concerns about existing IoUT protocol if in designing a perfect underwater communication model. Terrestrial channel models are replaced by practical underwater channel models. Therefore, existing IoUT protocols need to be revised and refined.

Researcher can apply this channel model to explore the various parameters like operating frequency, transmission range and Doppler's effect on reliable data transmission. This channel model can be used to investigate the link budget analysis for designing routing protocols. It can also be used to measure the performance of other communication protocols that can be observed by investigating the successful packet delivery ratio, average end-to-end delay, and energy consumption.

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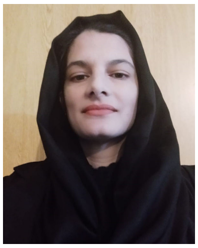

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